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Flexural fatigue performance and electrical resistance response of carbon nanotube-based polymer composites at cryogenic temperatures

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ABSTRACT

We study the flexural failure and electrical resistance change of carbon nanotube (CNT)-based polymer composites under cyclic loading at cryogenic temperatures. Fatigue tests were performed on CNT/polycarbonate composites at room temperature and liquid nitrogen temperature (77 K) using the three-point bending method, and the measurements of the specimen electrical resistance were made during the tests. Also, the specimen fracture surfaces were examined by scanning electron microscopy (SEM) to verify the failure mechanisms of the nanocomposites. The dependence of the mechanical and electrical responses of the nanocomposites on the temperature and the nanotube content was then discussed.

1. Introduction

Carbon nanotubes (CNTs) have attracted significant interest due to their exceptionally superior physical and mechanical properties. These properties combined with high aspect ratio (length/diameter) and low density suggest that CNTs may hold promise as nanofillers in polymeric materials for the next generation of multifunctional, high-performance engineering composite systems [1]. CNT-based polymer composites also appear to have potential for widespread applications [2–4], and an in-depth understanding of the nanocomposite performance in a variety of loading and environmental conditions is therefore necessary in order to fully explore their potential for engineering applications. Numerous studies on the physical and mechanical behaviors of CNT-based polymer composites have appeared in the literature [5,6]. However, most of the available studies on CNT-based polymer composites are limited to their behavior at room temperature and there is still a lack of investigations related to the nanocomposite response at cryogenic temperatures. Recently, our research group evaluated the mechanical performance of multi-walled nanotube (MWNT)/polycarbonate composites subjected to tension [7] and compression [8] in a cryogenic environment through experiments and multiscale simulations.

Structural health monitoring is a procedure for nondestructively identifying the current state of a component or system, and there is a significant interest in the development of techniques for such monitoring. Many researchers have investigated the electrical resistance-based deformation or damage sensing ability of CNT-based polymer composites [9–13]. The principle behind this is that the deformation or the damage initiation and evolution can lead to changes in the electrical resistance of CNT-based polymer composites. Furthermore, deformation (strain) sensors are the most important for determining long-term structural reliability. Thus, the electrical resistance-based sensing method provides the possibility of real-time health monitoring, which ensures the safety and reliability of engineering structures.

In practical situations, flexure is one of the most common types of loading for structures. In order to facilitate the development of multifunctional composite systems based on CNTs for engineering applications, the flexural fatigue performance of CNT-based polymer composites is of critical concern. In this paper, we investigate the fatigue and electrical resistance responses of CNT-based polymer composites subjected to flexural fatigue loading at cryogenic temperatures. Flexural fatigue tests were conducted on MWNT/polycarbonate composites at room temperature and liquid nitrogen temperature (77 K). During the tests, the electrical resistance of the specimens was measured. Also, the fracture surfaces were examined by scanning electron microscopy (SEM) in order to assess the failure mechanisms of the nanocomposites.

2. Experimental procedure

2.1. Material and specimen preparation

In this work, nanocomposites consisting of MWNTs (10–40 nm diameter, 5-20 μm length) and a polycarbonate matrix were em-

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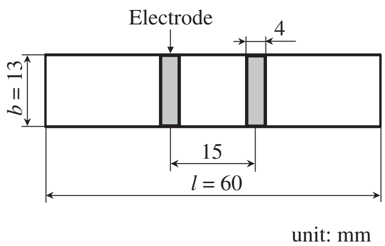

Fig. 1. Geometry and dimensions of flexural test specimen with thickness $t = 2.4$ mm.

ployed for the tests. The MWNT/polycarbonate composite samples were obtained from a commercial supplier (Takiron Co., Ltd., Japan). The nanocomposite samples were prepared with different MWNT weight fractions of 2.5 and 5.0 wt.%. Scanning electron micrographs revealed that the MWNTs were randomly oriented within the polycarbonate matrix [14].

The specimens for flexural tests were machined from the sample plates to the dimensions shown in Fig. 1. The specimens had a length (l) of 60 mm and a width (b) of 13 mm. The thickness of all specimens (t) was about 2.4 mm. All specimens from a plate were cut in the same direction. Note that the anisotropy of the composite properties may be small because of the random orientation of the MWNTs in the polycarbonte matrix. Conductive silver paint was attached on the top or bottom surface of the composite specimens as electrodes, in order to separately measure the surface electrical resistances on the tension and compression sides. The electrode width and the inter-electrode distance were 4 and 15 mm, respectively.

2.2. Testing method

Flexural static and fatigue tests were conducted at room temperature and 77 K using a 30 kN capacity servo-hydraulic testing machine. The composite specimens were tested under a three-point bend configuration utilizing center loading on a simply supported beam, according to the general recommendations of the standard test method ASTM D 790 M [15]. A span to thickness ratio (s/t) of 16 was chosen for static and fatigue tests. Testing at 77 K was accomplished by submerging the test fixture and specimen in liquid nitrogen at atmospheric pressure in a dewar. In practice, two or three specimens were tested for each material and condition, as shown in Table 1.

First, the composite specimens were monotonically loaded under displacement control at a rate of 0.6 mm/min to determine the static reference load values P_r for fatigue tests, i.e., flexural yield load at room temperature and flexural failure load at 77 K (see the details in Section 3). The flexural static tests were performed

Table 1
Number of specimens.

		Number of specimens	
		Static tests	Fatigue tests
RT	2.5 wt.% MWNT	2	3
	5.0 wt.% MWNT	2	2
77 K	2.5 wt.% MWNT	2	3
	5.0 wt.% MWNT	2	2

Table 2
Flexural static test results.

		P_r (N)	$\bar{P}_r$ (N)
RT	2.5 wt.% MWNT	135	136
		137	
	5.0 wt.% MWNT	143	146
		149	
77 K	2.5 wt.% MWNT	296	302
		307	
	5.0 wt.% MWNT	277	279
		281	

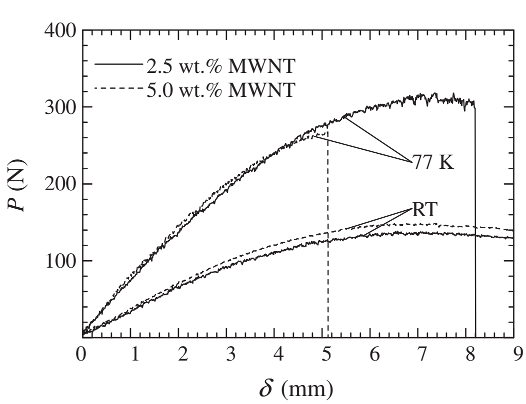

Fig. 2. Flexural static load–deflection curves.

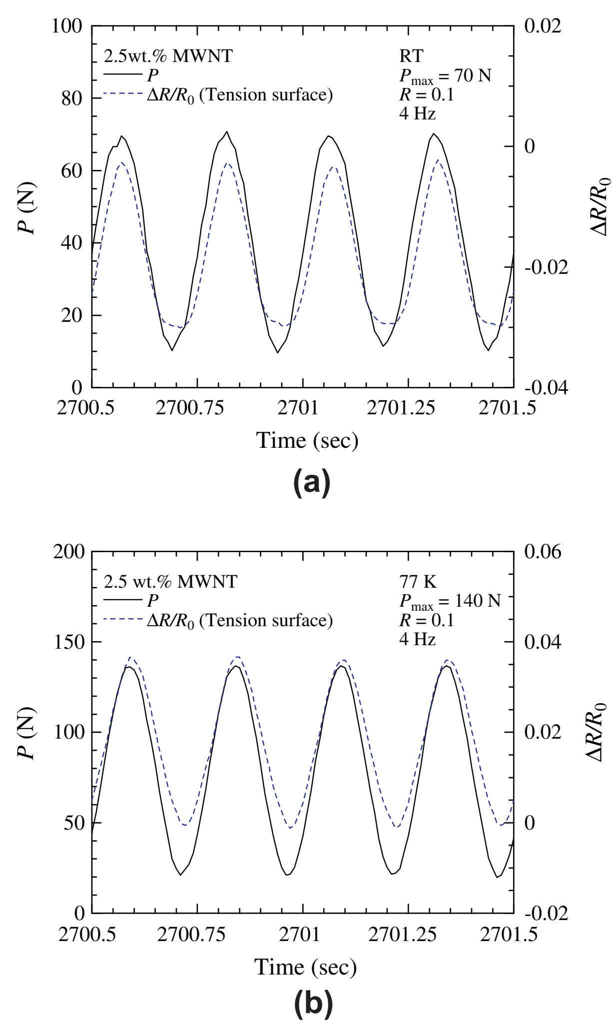

Fig. 3. Load and normalized resistance change on the tension surface versus time for the 2.5 wt.% MWNT/polycarbonate composite specimens at (a) room temperature and (b) 77 K.